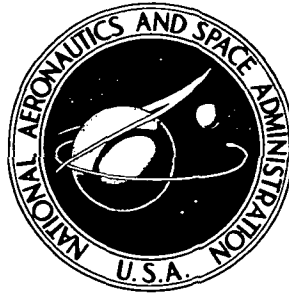


**NASA TECHNICAL
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**COMMUNICATIONS TECHNOLOGY SATELLITE
OUTPUT-TUBE DESIGN AND DEVELOPMENT**

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SUMMARY

The design and development of a 200-watt-output, traveling-wave tube (TWT) for the Communications Technology Satellite (CTS) is discussed, with emphasis on the design evolution during the manufacturing phase of the development program. Possible further improvements to the tube design are identified.

INTRODUCTION

The advent of the space age opened many possibilities for global communications: television from space, disaster warning, navigational assistance, data transmission, and others. Many of these activities have already been realized in presently operating systems. However, a characteristic feature of these systems is a relatively low power output (5 to 20 watts) from the space-borne transmitter, which eliminates the possibility of reception by individual users with inexpensive equipment. The successful development of the efficient and powerful, 200-watt-output, traveling-wave tube (TWT) and the deployment of the Communications Technology Satellite (CTS) in synchronous orbit will for the first time bring television directly to many small ground receivers in North America. Even more powerful tubes have now been developed in Germany, and the export potential of communication and/or broadcasting satellites of the CTS type to many regions of the world is very high. The TWT developed for the CTS project is a pioneer in a series of future, high-power, space transmitters. A brief history of the research and development of the 200-watt TWT follows. Major specifications and measured performance of the flight tube are compared in table I.

Because of the anticipated difficulty of developing a radiation-cooled, traveling-wave

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tube of high efficiency for operation at a frequency of 12 gigahertz, two 1-year contracts for research and development were awarded in the spring of 1972. Each contractor was required to fabricate eight tubes and deliver four operable tubes at the end of the year of effort. These tubes were then to be tested and compared, and the better design was to be selected for further development.

Two independent designs (herein denoted A and B) for a coupled-cavity, traveling-wave tube were proposed and developed by the two contractors. Design A had the higher perveance ($0.125 \times 10^{-6} \text{ AV}^{-3/2}$), with a band center located at a phase shift per cavity of 1.35π and a cold-to-hot bandwidth ratio of 5:1. Design B, on the other hand, had a very large bandwidth ratio of 15:1 to reduce circuit losses and placed the band center at a phase shift per cavity of 1.2π in order to raise the interaction impedance. The perveance of design B ($0.0625 \times 10^{-6} \text{ AV}^{-3/2}$) was half that of design A. Both designs incorporated velocity tapers that significantly reduced the circuit phase velocity. Consequently, serious difficulties were encountered with reflections, instabilities, and circuit losses.

Both design-A and design-B tubes were to be produced with 4° apertures in the collectors of one half of the tubes and 6° apertures in the collectors of the others. A final decision on the collector apertures of the flight tube was also to be made at the end of the year of research and development.

As it turned out, the yield experienced by both contractors during the year of research and development was much lower than expected. Two operable tubes of design B and one of design A were available on which to base required decisions. The single design-A tube suffered from slot-mode oscillations at zero drive, but performed well at saturation. The two design-B tubes did not oscillate and performed well enough to undergo extensive bench tests. These tests revealed the existence of the following problems or deficiencies:

(a) Frequency positioning was incorrect, with a tendency for the power and gain peaks to be below the lower edge (12.038 GHz) of the frequency band, and with power and gain deficiencies at the upper edge (12.123 GHz).

(b) The small-signal gain variation across the specified frequency band (12.038 to 12.123 GHz) was about 10 decibels, well in excess of the specified ± 1.5 decibels.

It was thought that the defects noted in the two design-B tubes could be easily corrected in future tubes, and design B was chosen for the flight tube.

The two design-B tubes available for testing had 6° apertures in the collector. The single design-A tube had 4° apertures in the collector. Since the A and B designs had much different beam perveance, the relative collector efficiencies of the available design-A and design-B tubes could not be used to determine which aperture size was superior in the design-B tube. However, preliminary data were available on a third design-B tube undergoing testing at the contractor's plant. This tube had 4° apertures in

the collector and seemed to have a higher collector efficiency than did the two design-B tubes (6° apertures) already tested. This third tube failed catastrophically during testing soon thereafter. This summarizes the pertinent information available at the time a decision on aperture sizes had to be made. The collector aperture size chosen for the flight tube was 4° .

During the remainder of the program, a variety of technical and manufacturing problems continued to result in low tube yield (ratio of operable tubes to tube starts). The following are the most significant of these problems:

(a) Several tubes had improper band location and unacceptably high small-signal gain variation across the operating band.

(b) Several tubes exhibited zero-drive oscillation at the lower cutoff frequency of the coupled-cavity circuit.

(c) Many tubes had vacuum leaks.

(d) A cathode support sleeve failed due to time-temperature embrittlement.

(e) The cathodes in the early tubes were operating at much too high a temperature to meet the long-life requirements.

(f) Several of the U-tabs that supported the electrodes of the multistage collector failed during vibration tests.

(g) The tube collectors had a tendency toward excessive arcing when turned on after a long shutdown.

(h) The collector apertures of 4° selected for the flight design were found to be too small for optimum collector efficiency.

In the following sections, the design and processing procedure changes developed to address these problems are described. Because of schedular and monetary restrictions, not all possible corrective measures were implemented, but rather, only those most essential to launching and operation of the Communications Technology Satellite. The general electrical and mechanical characteristics of the tube are described in reference 1. Other aspects of the design and performance of the traveling-wave tube are described in references 1 to 7; other components of the Communications Technology Satellite are described in references 8 to 14.

GUN AND CATHODE DEVELOPMENT

During the development of the flight tube from the prototype tubes (2005 and 2006), a series of gun and cathode problems became apparent. These problems and their effected solutions are reported in the following sections.

Redesign of the Cathode Structure

The original cathode structure in the prototype tubes had a Spectra-Mat type "B" impregnated tungsten cathode pellet contained in a molybdenum sleeve that was 0.025 millimeter thick, 4.17 millimeters in diameter, and approximately 7.6 millimeters high. This type cathode was used in all the tubes fabricated through February 1974. In that period, tube 2005 developed unstable electron emission problems during testing. When this tube was dismantled for examination, the molybdenum sleeve, which is very brittle, was found to be faulty. This finding, as well as the concern that the brittle cathode sleeve might not withstand vibration testing, led to its redesign. The revised design substituted a molybdenum-rhenium alloy (50 weight percent of each) for the molybdenum sleeve material. The dimensions of the sleeve were unchanged. This alloy, which is ductile, offered a satisfactory solution to the problem.

Preparation and Processing of Guns and Cathodes

Because of the stringent life requirements of the space tube in the CTS program, it was obvious early in the program that the processing of the cathodes should be carefully controlled to give maximum life. An examination of the processing schedule for electron guns, instituted early in 1974, showed that the cathodes were subjected to a number of rigorous processing procedures which could adversely affect cathode life. The following two procedures were determined to unnecessarily shorten cathode life.

(a) After assembly, the cathodes in the gun were subjected to three heating cycles, each followed by exposure to air, before storage.

(b) Stringent activation schedules subjected the cathodes to very high temperatures of 1200°C for 3 hours or more.

These procedures were reviewed and revised so that essential needs were met and the adverse effects were minimized. The following revised procedures were adopted:

(a) After assembly, the cathodes in the gun were subjected to only two heating cycles. This step was further revised, in March 1975, to only one heating cycle.

(b) The activation schedule was changed so that the activation procedure consisted of heating the cathode to 1200°C for only 10 minutes at a time (hot shotting), for a maximum of 1 hour.

Cathode Operating Temperature

The prototype tubes had to operate at temperatures considerably above 1125°C to maintain emission of 0.5 A/cm^2 . This is not an unusual occurrence in commercial

terrestrial tubes but it was a real problem for the flight tubes, because cathode life would be adversely affected. Decisions were made to improve processing (discussed in the following section) so that poisoning and gas effects would be minimized. As a result, a basic requirement established for the tube was that the cathode operating temperature had to be kept below 1100°C to achieve a minimum operating lifetime of 2 years.

TUBE PROCESSING

The processing procedures used in the early stages of the development program proved to be inadequate. Internal arcing and gas evolution were encountered with some tubes during bench testing. This outgassing and arcing became much worse during thermal tests in a vacuum environment.

This gas evolution problem was corrected by establishment of a rigorous processing schedule for the flight-model tubes. After assembly, the tubes were baked out at 450°C for approximately 30 hours, while the collector jacket was simultaneously heated to 600°C . After the tube was pinched off at the bakeout station, the cathode was activated, and the beam was focused. The tube was then processed by a pulsing technique, starting at a 0.1-percent duty cycle. The tube was aged by slowly increasing the duty cycle as the tube degassed until continuous operation was attained. At this point, the collector jacket temperature was slowly increased to a maximum of 300°C , and the collector jacket was degassed further. If the gas evolution was too high during continuous operation, pulse techniques were again used until the tube was ultimately degassed. The final criterion for operation, before the tube was sealed off from the processing vacuum pump, was that the tube operate continuously, with no arcing, with the collector jacket at 300°C , and with the gas pressure, as measured in the tube ion pump, less than 10^{-8} torr.

CIRCUIT DESIGN

The coupled-cavity radio-frequency circuit is the same, with minor changes, as that described in reference 1. The 85-megahertz-wide CTS band is centered near a phase shift per cavity of 1.2π in all sections of the tube. The number of active cavities in each section is shown in figure 1. The three gain sections are separated by severs. The three velocity taper sections are separated by transition regions in which the phase velocity (or periodic length) changes gradually from one cavity to the next. Each sever consists of two modified cavities each containing tuning stubs and sever loads. Sever loads are 40 percent silicon carbide (SiC) and 60 percent beryllium oxide (BeO). For-

ward and backward circuit waves are completely terminated at a sever, since there is no coupling slot in the wall between the two sever cavities. Two additional cavities adjacent to the input and output couplers and on each side of the two severs are modified for impedance-matching purposes. These cavities have extra-long coupling slots, and thus extra-wide cold bandwidth, and provide a reduced contribution to the gain of the tube.

As compared to the design of reference 1, some minor changes in parts dimensions and fabrication procedures were required to achieve the desired placement of the CTS hot band within the circuit cold passband. Tubes produced early in the program had a tendency to have maximum gain and efficiency below the CTS band and small signal gain varying rapidly with frequency across the CTS band. Furthermore, the frequency-response characteristics were rather unrepeatable from tube to tube. Cold-test measurements indicated that the circuit passband shifted downward, by a nonrepeatable amount, during each braze operation. Because additional braze operations were used to repair leaks and other defects, the number of times a tube was brazed varied from two to as many as four. Even prior to the first braze, cold-test measurements showed a misalignment of up to 150 megahertz between the circuit passbands in different sections of the tube.

The nonrepeatability was reduced by improved parts quality control and standardization of the braze operation. Repair brazes were no longer allowed. Thereafter, the downward shift of the circuit passband due to the two allowed braze operations was a fairly consistent 50 ± 10 megahertz. The circuit passband in various tube sections was raised or lowered as required by altering cavity diameter by amounts up to 0.25 millimeter. Thus, before the braze operations, the circuit passband was well aligned throughout the tube, about 50 megahertz higher than the desired final frequency range. Figure 2 shows the resulting improvement in gain flatness, and figure 3, the improvement in saturation output power in the CTS band. It should be noted that careful alignment of the passbands of the various tube sections also produced an undesirable result. A severe velocity taper in a coupled-cavity traveling-wave tube may lead to regenerative oscillations near the lower cut-off frequency (π point) of the velocity-taper section of the tube. The reasons are discussed in reference 2. This regenerative effect was present in the early tubes and led to unacceptable variation in small-signal gain. In later tubes, with the passbands of the various sections better aligned, the regenerative frequency range was well below the operating CTS band, and gain flatness within the CTS band was quite acceptable. However, the resulting approximate alignment of the π points aggravated the regeneration in the tube output section. A high percentage of the later tubes were subject to zero-drive oscillation near the π point and had to be discarded.

TUBE MECHANICAL AND THERMAL DESIGN

The flight tube (2022 R-1) is shown in figure 4. A cross section of the flight tube is shown in figure 5. The tube is mounted to the spacecraft by the tube body support structure so that the collector enclosure protrudes outside the spacecraft thermal envelope and can radiate directly to space. The mechanical and thermal design of the depressed collector are described in another section of this report. The following is a description of the mechanical and thermal design of the tube body and some of the fabrication problems encountered during tube manufacture.

The tube-body thermal design requirements are that the tube body be able to absorb the heat generated by radio-frequency losses in the circuit (≈ 70 W), by beam interception (≈ 30 W), and by the cathode heater (6 W). This heat is conducted by the copper circuit parts to bus bars which are cemented by silver epoxy along the length of the tube body. (Originally, these bus bars were soldered to the tube body with indium solder, but this process was found detrimental to the tube operation.) The heat is conducted from the bus bars to the tube base by aluminum saddles which are rigidly bolted to the bus bars and base. Indium foil shims are used between the bus bars and the saddles and between the saddles and the base (see fig. 6).

A heat choke between the collector and the tube body is incorporated in the thermal design in order to prevent heat generated in the collector from leaking back to the tube body. The heat choke consists of a thin, stainless-steel (low thermal conductivity) bellows vacuum enclosure, with the collector supported on small, thin-wall, stainless-steel tubes. The thermal design of both the heat choke and the tube body have remained essentially unchanged during the program.

The tube mechanical design requirements are that the tube body structure support the cantilevered collector through the launch vibration and acceleration environment. The tube body by itself is not designed to carry the structural loads imposed by the cantilevered collector. It was therefore necessary to build an exterior structure between the collector and the tube base which would hold the entire structure rigid while transmitting the mechanical loads of the cantilevered collector to the tube body base. The interconnecting structure selected is essentially a box-beam truss which surrounds the tube body (see fig. 4). The radio-frequency input and output waveguides pass through the openings in the truss structure. The design of the truss has not been changed from the original except for the addition of diagonals to stiffen some open truss sections.

The radio frequency input and output waveguides were originally supported on thin sheet-metal brackets. Since this waveguide support configuration did not survive vibration, it was necessary to redesign the brackets to a more rigid, machined-aluminum design in order to survive the flight vibration environment.

REFOCUSING SECTION

Before the spent electron beam enters the multistage collector, it is reconditioned in a refocusing section. The refocusing section is essential for the highly efficient operation of multistage collectors. Its operation is described in references 3 and 4.

The refocusing field was implemented in the tube by means of permanent magnets. A field reversal between decay field and plateau field was incorporated in order to minimize magnetic leakage fields into the collector in experimental tubes, but was not used in flight-model tubes. There is now substantial analytical and experimental evidence showing that reversed plateau and decaying fields as realized from permanent magnets are as effective in refocusing the beams as are unreversed fields established with solenoids. (Permanent magnet refocusing has been implemented in several commercial communications and counter-measure tubes. Also, see ref. 5.)

MULTISTAGE COLLECTOR

The multistage collector is a key component in achieving high efficiency. Its basic concepts and functioning are described in reference 4, and its performance in experimental CTS tubes is described in reference 1. It consists of nine depressible collector electrodes and one electrode at ground potential, as shown in the schematic of figure 6.

The voltages of the available number of collector electrodes were selected to achieve maximum efficiency enhancement at saturation. This was determined by the kinetic-energy distribution of the spent beam as predicted by an approximate computer analysis. Later tests showed the predetermined collector voltages to be within 1 or 2 percent of true optimum.

The position of the collector electrodes was chosen to achieve essentially a uniform electrostatic deceleration field in the most negative collector region and a very weak decelerating field in the vicinity of the injection hole. The length of the trajectories is much larger than the radius of the beam at injection, which makes the beam appear as a point source. The number of collector elements was chosen as nine in order to compensate for uncertainties in predicting the spent-beam distribution at the time of conceptual design. After experimental evaluation, it became apparent that elimination of four electrodes with the least currents would reduce the collector efficiency by only two percentage points. This loss could, in turn, be recovered by improving the collector design, as described later in this section.

Velocity sorting is achieved by radial deflection forces caused by the conical shape of the collector electrodes; the endspike at cathode potential provides additional radial deflection which acts mainly on the high-energy electrons. Backstreaming of secondary

electrons is almost absent because of automatic suppression in negative fields (ref. 6). At saturation, the highest collector efficiency was 82.5 percent, which was achieved in one experimental CTS tube. The aperture cone, that is, the conical surface on which the openings in the electrodes terminate, was assigned two experimental values: 6° and 4° . From these two values a single one which produced the best efficiency was to be selected for the final flight design. The values of 6° and 4° for the experimental design were selected from single-cavity calculation of electron trajectories for the (low-perveance) CTS tube. The radial-velocity reduction due to the action of the refocusing section was taken into account in the computation. At the time of the conceptual design of the traveling-wave tube, it was generally estimated that the circuit losses would be approximately 10 percent of the internally generated radio frequency power. Experimental results showed this number to be as high as 30 or 40 percent. The resultant increase in radio frequency power that had to be extracted from the beam led to greater axial and radial velocity dispersion than originally estimated. It became evident after the completion of the R&D phase of the program that aperture angles of approximately 7° , rather than the 6° originally estimated, would be required for optimum performance.

However, due to schedular pressure, a freeze had been imposed on design B in May 1972 without an adequate evaluation of the 4° apertures. The 4° aperture size had been selected for the final design B on the basis of then-available data and partial test results from tube 2007, which had 4° apertures. After collector data from two more tubes became available, it became evident that the 6° apertures would have been the better choice.

The evaluation of collector performance and newer analytical results indicate that the design and, very likely, the performance of the collector could be improved by the implementation of the following changes: (a) increasing the aperture angle from 4° to 7° , and (b) increasing the angle of the conical electrode at cathode potential (see fig. 6) from 60° to 70° , thereby making the design less dispersive for the high-energy electrons and, consequently, more efficient in the radio-frequency mode as well as in the direct-current mode. Financial and schedular constraints prevented implementation of these collector improvements in the design of the flight tube, since they were not essential to the success of the flight program.

COLLECTOR MECHANICAL AND THERMAL DESIGN

The electrical theory of operation and performance of the multistage collector has been described previously. The 10 collector electrodes are circular plates spaced about 1 centimeter apart and held in position by six equally spaced alumina ceramic insulation rods. This collector-plate assembly is attached to a cylindrical vacuum en-

closure by supports at each end of each of the six ceramic rods.

The primary thermal design requirement for the collector is that it radiate up to 150 watts of heat dissipated by the spent electron beam. This thermal energy is radiated from the collector plates to the collector vacuum enclosure and then reradiated to space. Since the spent electron beam velocity distribution varies for a saturated electron beam as opposed to a beam without radio-frequency drive, the collector plates are required to radiate the nonuniform heat loads. The collector structure must also be capable of withstanding the nonuniform thermal stresses created by this heat loading. Local hot spots on the collector plates are estimated to have temperatures up to 400°C . The collector vacuum enclosure operates at approximately 200°C . The collector structure and collector support system is designed to withstand vacuum bakeouts at 600°C .

The mechanical design requirements for the collector support system are that it transfer a steady-state peak acceleration load of 16 g's along the collector axis and 3.5 g's laterally. The support system is also required to withstand vibration environments in which the peak lateral acceleration force at the collector is 35 g's in the frequency range between 110 and 120 hertz. The system also should not have resonant frequencies which would couple with the satellite vibration input frequencies. In addition, the collector support system needs to withstand the operational and vacuum bakeout temperature excursions and their accompanying thermal distortions of up to 1.32 millimeter differential diametral expansion and up to 0.66 millimeter differential longitudinal expansion between the collector and its supporting vacuum enclosure.

The original collector support system consisted of stainless-steel U-tabs welded between the ceramic rods of the collector and the vacuum enclosure at each end of the collector (see fig. 7). These collector supports allowed the collector to expand freely both radially and longitudinally with respect to the enclosure. However, the collector-system vibration natural frequency was too low with respect to that of the entire tube assembly, and high amplification factors were recorded on the collector during vibration. During vibration qualification, the U-tab supports cracked and failed, and a redesign effort became necessary.

The collector support system was redesigned and successfully met the requirements of high natural frequency coupled with free radial and longitudinal expansion. The design consists of fixing the base of the collector (at plate 1) in longitudinal position by means of six radially pointing pins at each of the six collector ceramic rods (see fig. 8). This allows free radial expansion but no longitudinal or rocking motion of the collector. Radially pointing forks (fig. 9) are used in contact with the ceramic rods at the opposite end of the collector (at plate 10). These forks restrain the collector laterally but not radially or longitudinally. Thus, the collector can freely expand and contract both radially and longitudinally with respect to the collector support enclosure but has high

resonant natural frequencies (greater than 800 Hz) in both directions.

Since the pins and the forks of the support system act as bearings during thermal cycling, good vacuum bearing materials had to be used. Tungsten pins in zirconium-copper bushings were used at the pinned end of the collector, and stainless-steel forks riding directly on the alumina ceramic rods were used at the opposite end of the collector.

CONCLUDING REMARKS

The design of the 200-watt traveling-wave tube for the Communications Technology Satellite is discussed with emphasis on design changes required during the manufacturing phase of the program. It is evident that space tubes with multistage depressed collectors require special attention in the areas of quality control, tube and cathode processing, and collector mechanical design. Circuit losses in the velocity taper section were much larger than expected. Further possible design improvements in the geometry of the multistage depressed collector are identified.

Lewis Research Center,
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610-22.

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**TABLE I. - MAJOR SPECIFICATIONS AND MEASURED RESULTS
FOR TRAVELING-WAVE TUBE**

Parameter	Contract initial specification	Contract final specification	Measured result
Active frequency range (CTS band)	12.038 to 12.123 GHz	12.038 to 12.123 GHz	Greater than required
Saturated output power in CTS band	200 W minimum	180 W minimum	191 W
Saturated gain in CTS band	33 dB minimum	30^{+2}_{-1} dB	29 to 31 dB
Maximum small-signal gain variation in CTS band	± 1.5 dB	5 dB peak to peak	4.5 dB peak to peak
Overall efficiency in CTS band	50 percent minimum	50 percent minimum	44 to 50 percent

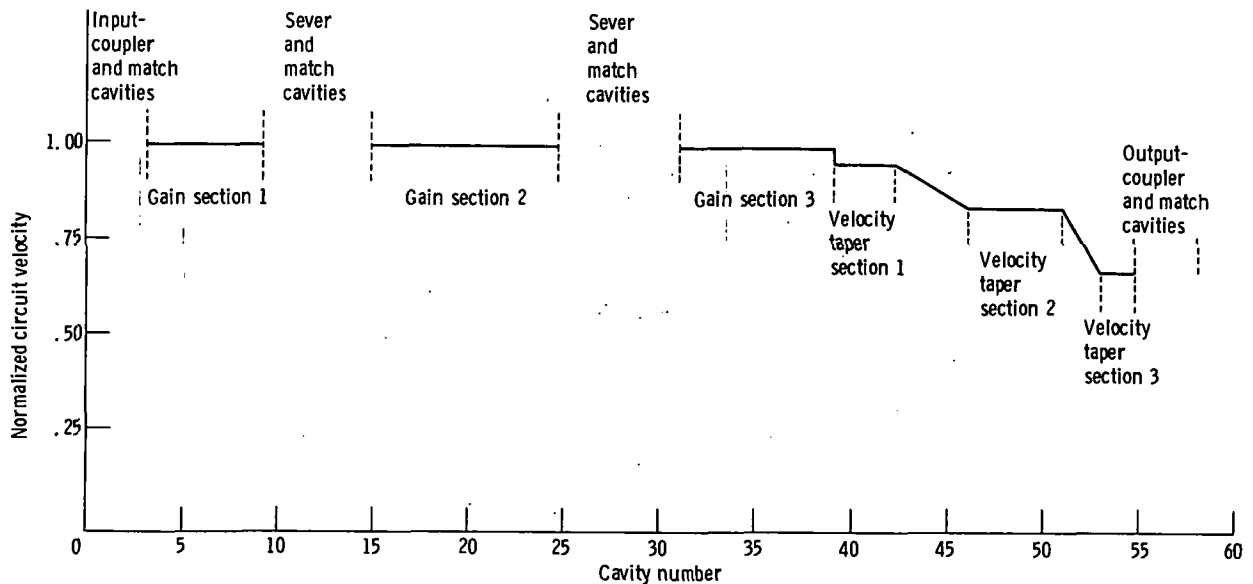


Figure 1. - Normalized circuit velocity as function of cavity number.

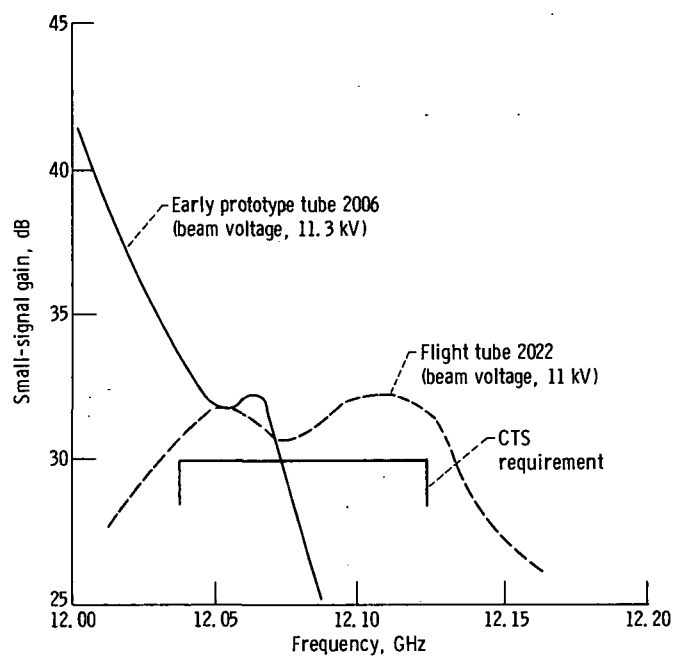


Figure 2. - Small-signal gain as function of frequency.

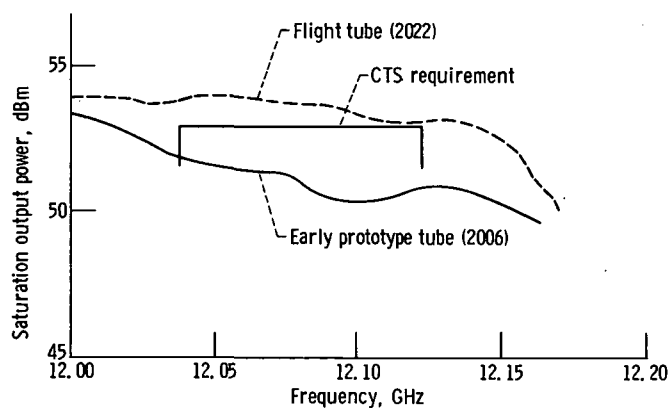
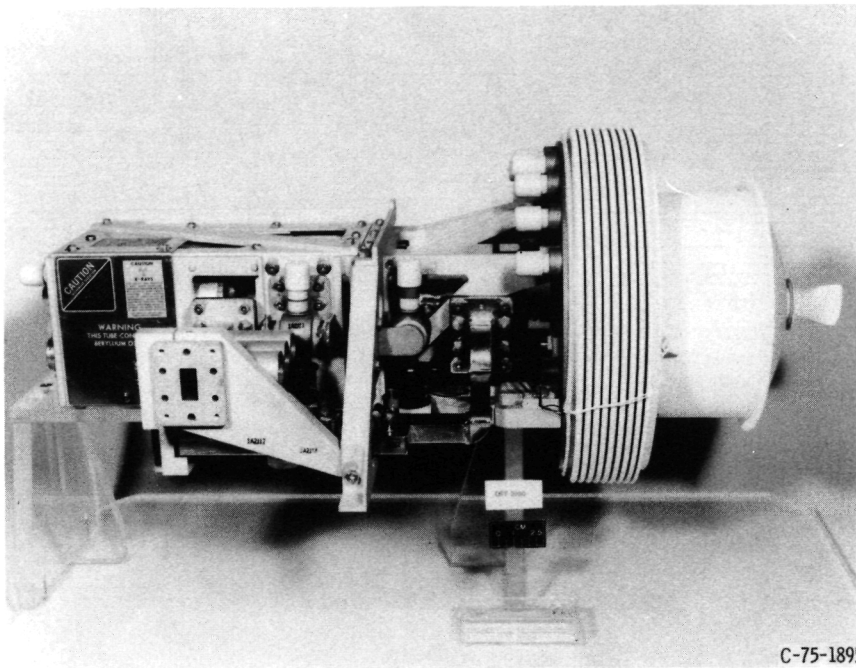
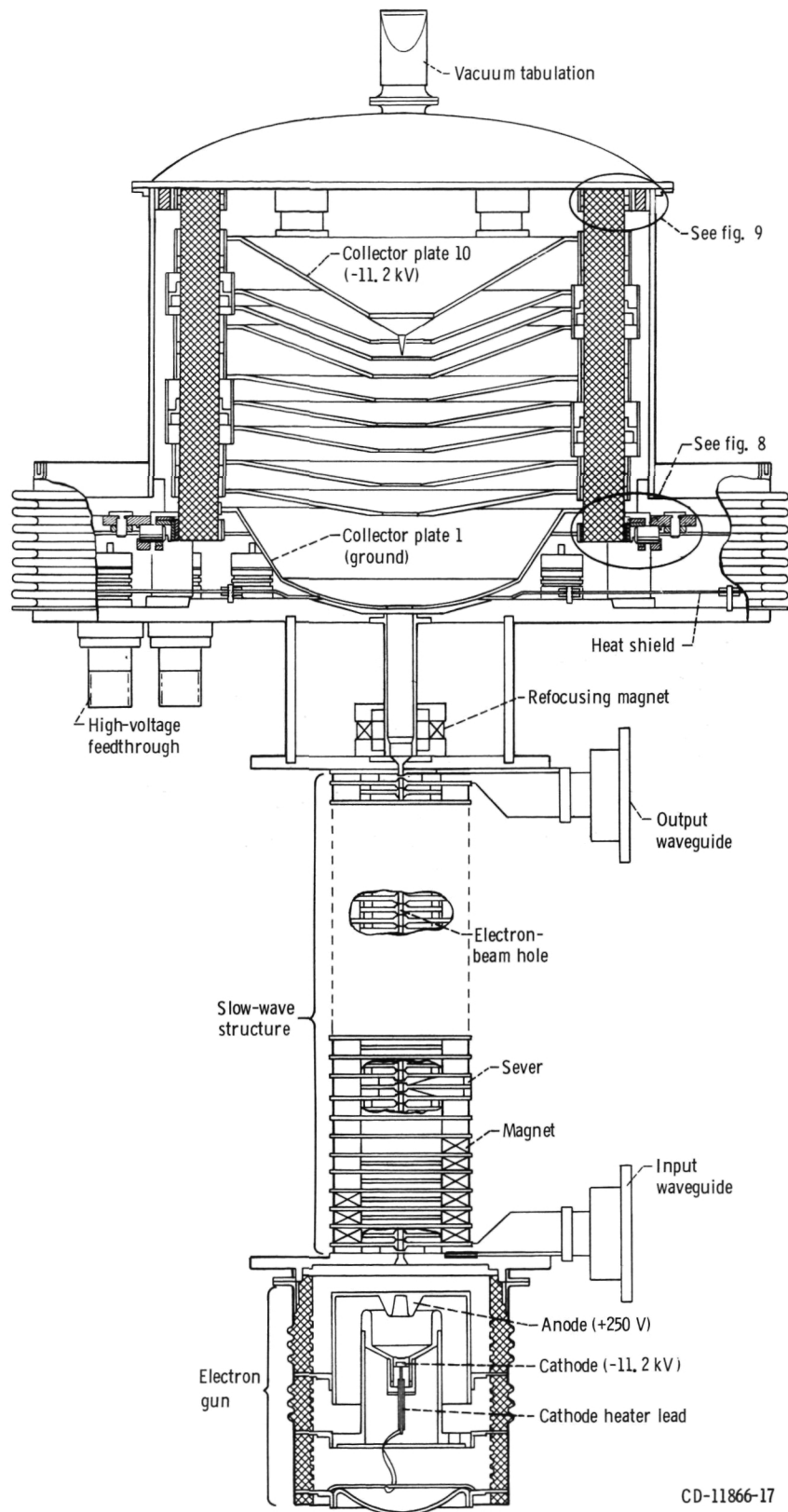


Figure 3. - Saturation output power as function of frequency.



C-75-1895

Figure 4. - Flight tube.



CD-11866-17

Figure 5. - Coupled-cavity traveling-wave tube with multistage depressed collector.

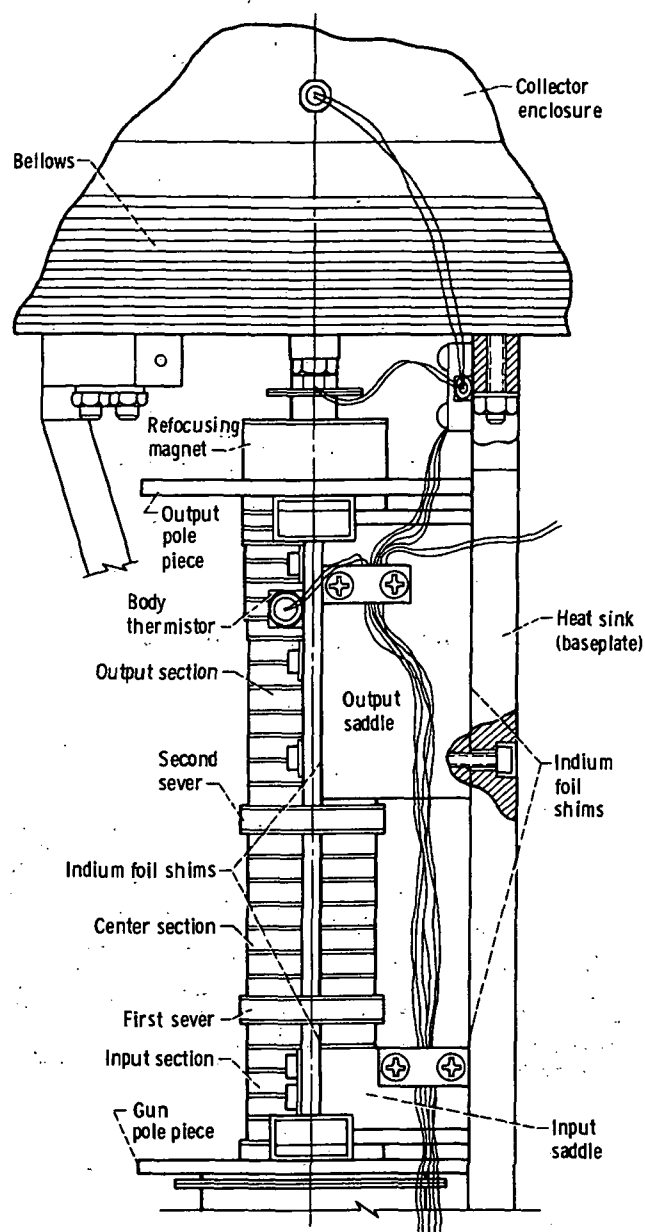


Figure 6. - Detailed view of coupled-cavity traveling-wave tube body.

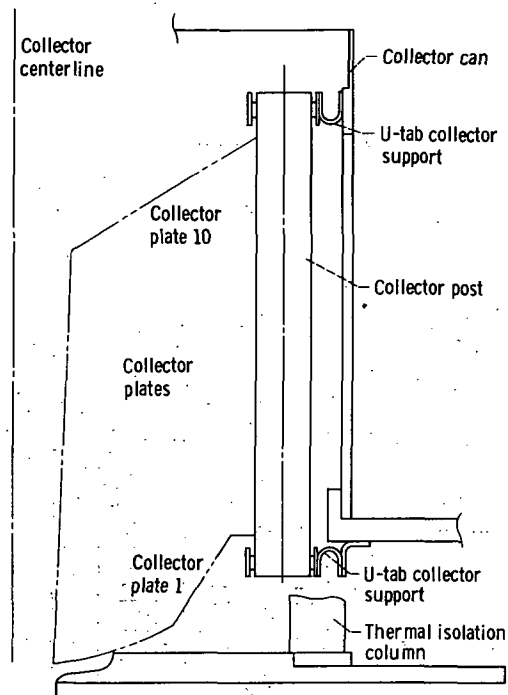


Figure 7. - U-tab collector support design.

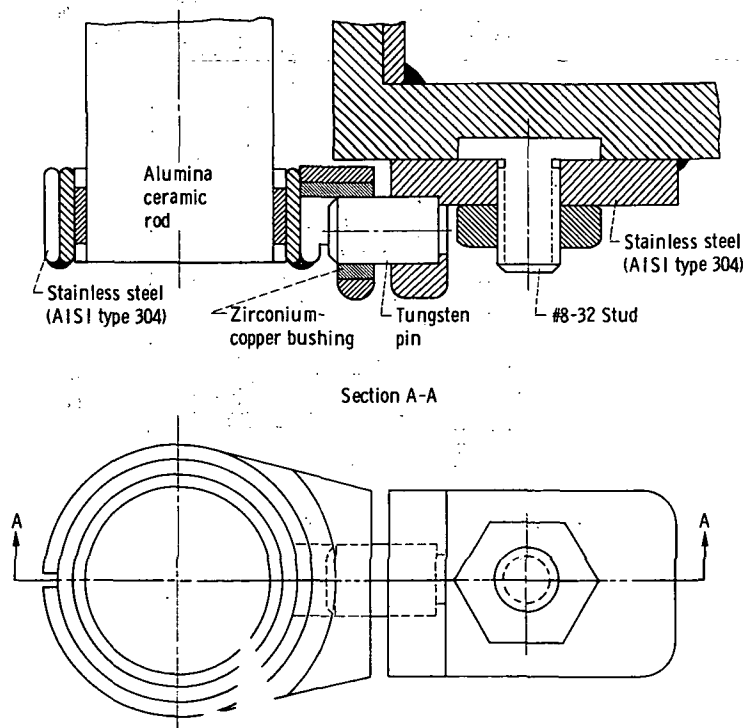


Figure 8. - Support system at base (near plate 1) of collector.

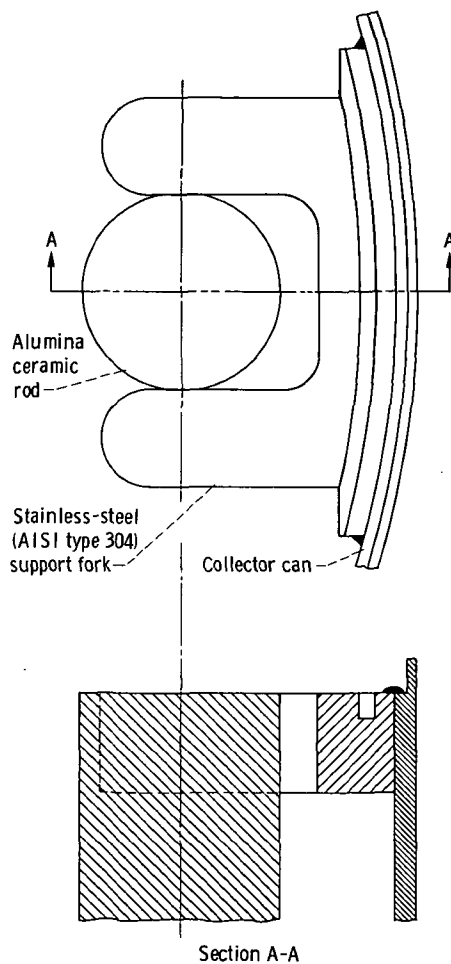


Figure 9. - Support system at top (near plate 10) of collector.



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